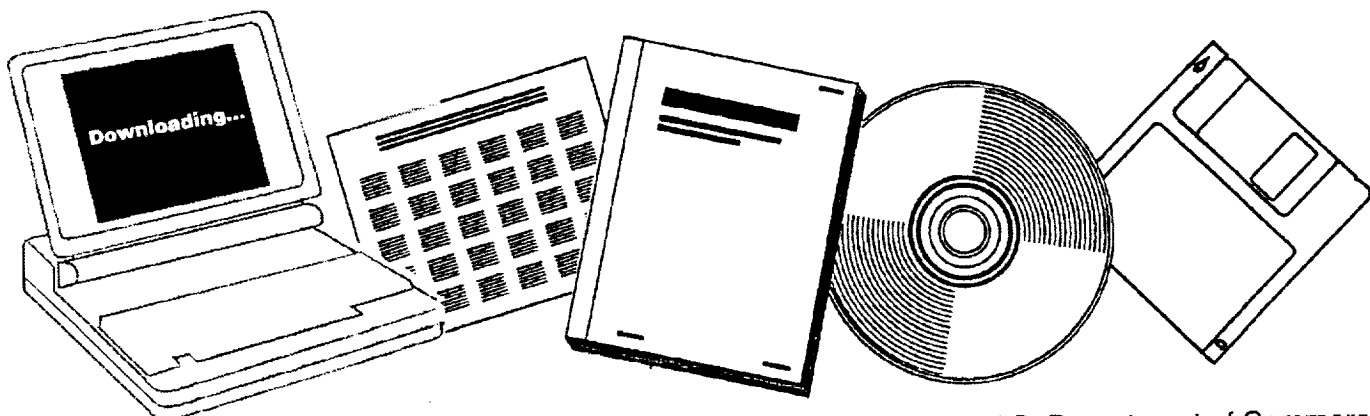




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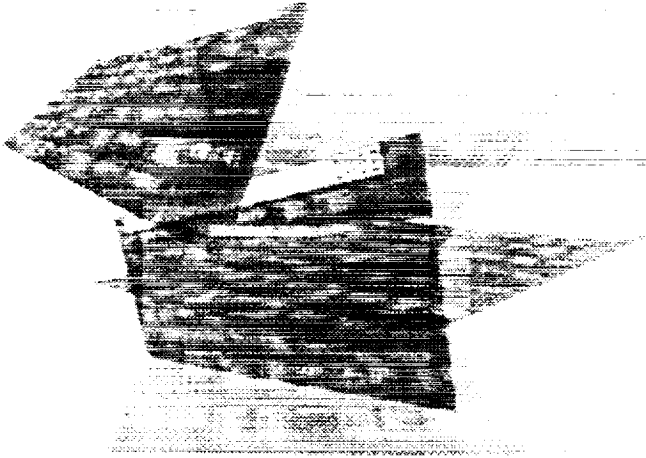
DIGITAL CONTROLLERS FOR THE VERTICAL CHANNELS OF A MAGNETIC SUSPENSION SYSTEM

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NASA Contractor Report 165684

DIGITAL CONTROLLERS FOR THE VERTICAL CHANNELS OF A MAGNETIC SUSPENSION SYSTEM

(NASA-CR-165684) DIGITAL CONTROLLERS FOR
THE VERTICAL CHANNELS OF A MAGNETIC
SUSPENSION SYSTEM (Southampton Univ.) 35 p
CSCI 14B

N81-26159

Unclass
63/09 26717

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Grant NSG-7523
May 1981



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Space Administration

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List of Symbols

- $A = K_p K_3 Z_{vH} / mR$
- $a = Z_{vH}^2 / mR$
- $b = Z_z / m$
- $D = d/dt$. Differential operator
- E = input to power amplifier, (volts)
- $E_p = K_p E$, output from power amplifier (volts)
- i = current in coils (amps)
- K = gain constant, (volt/volt)
- K_p = power amplifier gain, (volt/volt)
- K_{bs} = back E.M.F. constant representing induced voltage per unit rate of movement in the s th mode.
- K_3 = sensor sensitivity, volts per unit displacement.
- L = inductance of coil, (Henry).
- m = mass of suspended model. (kg)
- M_s = mutual inductance
- n = high- to low-frequency gain ratio for a phase advance filter
- R = resistance of coil and any series resistor, (ohms)
- T = time constant, (secs)
- $T_c = L/R$, coil time constant, (secs)
- V = output from pre-filter, (volts)
- x = model displacement in out-of-plane mode
- z = model displacement in Vertical Heave, (m)
- Z = Vertical Heave component of magnetic force, (N)
- $Z_{vH} = \frac{\partial Z}{\partial i} = \frac{\partial E_p}{\partial \dot{z}}$, V.H. force per unit change in coil current, (N/amp)
and also back EMF per unit velocity in V.H., (volt /m/s)
- $Z_z = \frac{\partial Z}{\partial z}$, change in force Z due to unit displacement, (N/m)
- θ = prefilter output representing Vertical Pitch rotation, (volts)

Superscripts

- * = sampled version of

DIGITAL CONTROLLERS FOR THE
VERTICAL CHANNELS OF A MAGNETIC
SUSPENSION SYSTEM.

1. - Introduction

The Magnetic Suspension and Balance System (MSBS) at the University of Southampton enables a model fitted with magnetic core to be suspended in a wind-tunnel, with control over the full six degrees of freedom of movement of the model. The system is described in Reference 1 and briefly in the next section of this report.

As part of a programme of work under NASA Grant NSG-7523, the controller used in the MSBS is being changed from an analogue version to a digital filter version. This report describes the first step in this conversion, in which two of the six degrees of freedom, viz vertical heave and pitch, have been fitted with digital versions of the analogue filters. These two channels then become digitally-controlled analogue systems.

The objective of this first step is a limited one. The analogue filters in the two channels had double phase advance transfer functions of form

$$K \left(\frac{1 + n_1 T_1 D}{1 + T_1 D} \right) \left(\frac{1 + n_2 T_2 D}{1 + T_2 D} \right)$$

The digital replacements aimed at similar transfer functions so that performance comparisons could be made, and experience gained in digital filtering.

An additional objective was to determine a mathematical model of the analogue parts of the system, from power amplifiers to pre-filter outputs in Figure 1, in particular for the vertical heave and pitch channels. Ultimately a more complete calibration of the suspension system will be needed since a knowledge of the magnetic forces and moments is necessary for the 'balance' function of the MSBS.

2 - Description of S.U. MSBS with Analogue Controller

2.1 General Description

The Southampton University facility is a six degree of freedom MSBS. Models can be controlled in vertical heave, pitch, lateral heave, yaw, fore-and-aft, and roll. The system consists of subsystems linked as in Figure 1 and identified as:-

- (1) Seven Coils arranged as in Figure 2 so as to produce a magnetic field which acts on the model to produce force and moment vectors in which all six components are controllable.
- (2) The model, fitted with magnetic cores which interact with the magnetic field.
- (3) A set of optical sensors, six in all arranged as in Figure 3. These monitor the position of the model. The information content as a whole is sufficient to give displacements of the model in all six degrees of freedom listed above. (Fig. 3 omits fore-and-aft and roll sensors.)
- (4) A pre-filter which processes the sensor signals so as to determine the model position as displacements in the six separate degrees of freedom.
- (5) A Controller consisting of a set of six comparators and compensating filters, one for each degree of freedom. The signals from these filters represent the six forces and moments required to be generated by the electromagnet coils.
- (6) A Translator, which routes the signals from the filters to the power amplifiers which drive the coils, in such a way that each signal will control one component of force or moment.
- (7) A set of seven power amplifiers, one for each magnetic coil.

The pre-filter, controllers and translator perform the signal processing

functions by means of analogue circuitry as described in Reference 1.

2.2. The Analogue Controller

Each degree of freedom is controlled by a separate analogue controller, on the assumption that there is little cross-coupling between these channels in the plant. The controllers take the form shown in Figure 4.

For vertical heave the controller's transfer function is

$$0.5 \left[\frac{1 + 0.031 D}{1 + 0.0033D} \right]^2 .$$

This was checked experimentally using a harmonic response method. The Bode Plots showing the experimental data appear as Figure 5.

For vertical pitch (rotation) the controller's transfer function is

$$0.15 \frac{(1 + 0.0367 D)}{(1 + 0.006 D)} \frac{(1 + 0.033 D)}{(1 + 0.0034D)} .$$

The harmonic response is shown in Figure 6.

2.3. The 'Plant' Mathematical model

The 'plant' in this context refers to Blocks 6, 7, 1, 2, 3, 4 in Figure 1, which is that part of the system which was left in its original form, mainly analogue.

The six inputs to this plant represent the controls for the six degrees of freedom of the suspended model, and the six outputs represent the measured displacements in these degrees of freedom. Over the displacement ranges permitted by the sensor system, the translator and pre-filter together ensure that there is little cross-coupling between the degrees of freedom, so that any one input produces only one output. The vertical heave (V.H.) and pitch rotation (V.P.) were chosen to be controlled by digital computer and so the plant for these two channels only are mathematically modelled. Both are described by the following analysis, although the symbols used correspond to the vertical heave motion:-

The power amplifiers supplying the electromagnet coils use a thyristor-switched three-phase supply. This gives a 150 Hz sampling system feeding the coils. However, at frequencies which are low compared with 150 Hz the amplifiers may be modelled as giving an output E_p proportional to their input E .

$$\text{Thus } E_p = K_p E. \quad \text{_____} \quad (1)$$

The voltage-current relationship for the coils is given by

$$E_p = iR + L \frac{di}{dt} + \sum_s M_s \frac{di_s}{dt} + Z_{vH} \dot{z} + \sum_s K_{bs} \dot{x}_s$$

$$\dot{=} iR + L \frac{di}{dt} + Z_{vH} \dot{z} \quad \text{_____} \quad (2)$$

where it is assumed that intercoupling between channels is small, both via mutual inductance M_s between coils and via back-EMF effects from model motions in channels other than vertical heave. The back-EMF constant Z_{vH} is equal to the change in force per unit change in current i .

The force on the model depends upon the current in the V.H. coils and upon the deviation of the model from its equilibrium position. The motion about the equilibrium position is governed by the equation

$$m \ddot{z} = Z_{vH} i + Z_z \dot{z} \quad \text{_____} \quad (3)$$

where the steady state forces are ignored since they are in balance in the equilibrium state.

Z_{vH} is the change in magnetic force per unit change in coil current.

Z_z is the change in lift force due to change of position. For vertical heave model is in unstable equilibrium when the coil current is constant so that Z_z is positive.

The pre-filter/sensor output V is proportional to the model position z , and a low-pass filter is included. Thus.

$$V = \frac{K_3 z}{1 + TD} \quad \text{_____} \quad (4)$$

Overall Plant Transfer Function

Eliminating i , z , E_p from equations (1) \rightarrow (4) leads to a transfer function relating pre-filter output V to power amplifier input E which is

$$\frac{V}{E} = \frac{A}{(1 + TD)(1 + T_c D)(D^2 + aD - b)}$$

$$\text{where } A = K_p K_3 Z_{VH}/mR$$

$$a = Z_{VH}^2/mR$$

$$b = Z_z/m$$

$$T_c = L/R$$

and it is assumed that $\frac{L}{R} \cdot \frac{Z_{VH}^2}{mR} \ll 1$. In fact $\frac{L}{R} \cdot \frac{Z_{VH}^2}{mR}$ is of order 10^{-3} .

Numerical values for the plant constants A , a , b , T_c were obtained by fitting the transfer function to experimentally obtained data. Since the plant is not controllable in its open loop form the loops were closed via the analogue controllers, and in this form the harmonic responses were obtained. These are shown on Nichol's Charts in Figures 7 and 8. Following the 'subtraction' of the controllers the resulting plant responses were deduced. These are shown on the Nichol's Charts and again in Bode Form on Figures 9 and 10.

The following transfer functions of the fourth order form shown in Equation 5 were deemed to be good enough fits to the experimental data over the frequency range 2 \rightarrow 25 Hz. (See Figures 9 and 10):

$$\text{Vertical heave 'plant': } \frac{V}{E} = \frac{4730}{D^2(1 + \frac{D}{40})(1 + \frac{D}{600})}$$

$$\text{Pitch angle 'plant': } \frac{V}{E} = \frac{8500}{D^2(1 + 0.019D)}$$

From a comparison with Equation 5 it may be seen that:

(a) the back-EMF term a and the positional stiffness term b play little part in stability aspects of the suspension system. The analysis of the term Z_z in Reference 1 indicates that the lateral stiffness has a greater value than the vertical stiffness but the term may be ignored when dealing with the stability of the suspension system over small angles to the tunnel axis.

(b) the mass (or inertia) of the model affects predominantly the term A in Equation 5 and so changes of model may be compensated by changes in controller gain.

3. Digital Controllers for Vertical Heave and Pitch

The controllers required were intended to be direct replacements for analogue filters having transfer functions:

$$\text{Heave: } \frac{E}{z} = 0.5 \frac{(1 + 0.031 D)^2}{(1 + 0.0033 D)^2}$$

$$\text{Pitch: } \frac{E}{\theta} = 0.15 \frac{(1 + 0.0367 D)(1 + 0.033 D)}{(1 + 0.006 D)(1 + 0.0034 D)}$$

Algorithms were based upon the difference equation approximations of the differential equations represented by these transfer functions. The difference equations for a single stage phase advance $\frac{1 + nTD}{1 + TD}$ are developed in Appendix A and appear as Equations A1, A2, A3. Each of the controllers consists of two stages of phase advance, and these are applied sequentially.

The constraints imposed were:

(a) The A/D converters were both 0-10 volt to 12-bit converters, giving a resolution of one part in 4096. Word lengths within the processor were normally 16-bit; double length words were used as necessary. The D/A conversion was 12-bit to 0-10 volts for Vertical Heave and 8-bit to 0-4 volts for Vertical Pitch.

(b) Fixed point integer arithmetic was used in order to achieve speed in processing. Fast floating point arithmetic was not available.

Care was needed to ensure that suitable scaling was used throughout the processing so as to avoid the extremes of very coarse resolution due to under-filling a register on the one hand, and of over-filling a register on the other hand. Double length arithmetic was used where appropriate within the algorithm.

(c) 1500 Hz sample rate was used - an arbitrary decision, but one which was safe in that the sampling had little effect upon system stability.

(d) Assembly level language was used for fast real-time processing (Macro eleven)

Vertical Heave

The controller used algorithms which approximate a transfer function

$$\frac{E}{z} = 0.5 \frac{(1 + 0.032 D)^2}{(1 + 0.004 D)^2}$$

The slight differences between this and the analogue controller were made in order to round off numbers in the binary code.

The algorithms used were:

$$\Delta_1 = z^*(k) - y_1(k-1)$$

$$y_1(k) = \{z^*(k) + 5y_1(k-1)\} / 6$$

$$y_2(k) = \{y_1(k) + 8\Delta_1\} / 2$$

$$\Delta_2 = y_2(k) - y_3(k-1)$$

$$y_3(k) = \{y_2(k) + 5y_3(k-1)\} / 6$$

$$E(k) = y_3(k) + 8\Delta_2$$

A listing of the computer programme is shown in Appendix B.

Vertical Pitch

The controller used algorithms which approximate a transfer function

$$0.2 \frac{(1 + 0.029 D)(1 + 0.032 D)}{(1 + 0.007 D)(1 + 0.004 D)}$$

The algorithms used were:

$$\Delta_1 = 8\theta^*(k) - y_1(k-1)$$

$$y_1(k) = \{8\theta^*(k) + 10y_1(k-1)\} / 11$$

$$y_2(k) = \frac{y_1(k)}{4} + \Delta_1$$

$$\Delta_2 = y_2(k) - y_3(k-1)$$

$$y_3(k) = \{y_2(k) + 5y_3(k-1)\} / 6$$

$$E(k) = \{y_3(k) + 8.42\} / 64$$

N.B. The algorithm takes account of the discrepancy between the 0-10 volt range of the input to the A/D, and the 0-4 volt output of the D/A.

A listing of the programme is shown in Appendix B.

Bode Diagrams for the above controllers are shown in Figures 11 and 12. In practice the sample - compute - hold process also introduces a phase lag, and the Bode Plots of the practically achieved controllers, from analogue input to analogue output, are also shown for the sampling frequency of 1500 Hz.

4. Discussion of the Digitally Controlled Suspension System

The performance of the suspension system with the digital controllers was similar in most respects to that with the analogue controllers. The stiffnesses, natural frequencies and damping ratios were comparable.

The major difference in performance was in the amount of noise in the system, or the effect of that noise upon model movement. There was more random movement of the model when using the digital controllers than when using the analogue versions. In vertical heave the amplitude of movement was of order ± 0.5 mm (2% of maximum displacement), whereas with the analogue controller there was virtually no movement.

Some tests were performed to establish the source(s) of noise and to reduce it or to reduce its consequences. Full diagnosis and elimination has not been completed since the electromagnet assembly has been dismantled and access to the equipment has been interrupted. However the following observations may be made.

(1) The suspension system controllers used throughout the work reported here have been ones which have very high ratios of high- to low- frequency gains. The double phase-advance system in vertical heave has a ratio of 100, and this inevitably calls for careful control of noise on the sensor signals, whether the controller is of analogue or digital form. A digital system is inherently more noisy than an analogue system and a direct replacement of a double phase-advance filter is not the best approach to digital control. An alternative form of controller is being studied.

(2) One source of noise was that picked up in the cables linking the computer with the rest of the hardware. These cables were of appreciable length, about 25 metres compared with very short lengths to the analogue controllers. In both cases the inputs to the controllers contained spikes picked up from the switching of the thyristors in the power amplifiers.

In the analogue system there was no special provision beyond clipping the amplitude of the spikes on the controllers' outputs.

On the digital system a low-pass (anti-aliasing) filter was included at the input to the A/D converter. The attenuation at the sampling frequency (1500 Hz) was such as to reduce spike amplitudes to the level of one bit ($\frac{10}{4096}$ volts) or less i.e. to less than the resolution of the A/D.

This produced a measure of improvement in the amplitude of the ambient model motion but it was still poor compared with the analogue system.

(3) A second source of noise generation is at the D/A, which gave an output with significant 1500 Hz repetition rate visible. This, together with mains hum (50 Hz) and thyristor-switching spikes, was present on the signal inputs to the power amplifiers. By contrast the analogue controllers' outputs contained only mains hum and the v.h.f. thyristor-switching spikes.

Since the power amplifiers have three-phase thyristor-switched controls they are sensitive to noise at their input. They operate in some sense as a sampling device and so have aliasing characteristics with a sampling frequency of 150 Hz. These power amplifiers work well with the analogue controllers despite evidence of v.h.f spikes at the controllers' outputs, but their response to the D/A signal is felt to be the major cause of the 'noise' on the model movement. Certainly an analogue computer simulation of a plant obeying the overall transfer function given in equation (5) exhibits no such noise when controlled by the same digital controller; the simulated plant did not include a representation of the sampling action of the power amplifiers.

Non-availability of the real plant has led to an interruption of the work aimed at full confirmation of the above and at improving the compatibility between D/A and switched power amplifiers. It is clear, however, that it is important to avoid noise generation at a D/A which is being followed by a sampling device, especially if the sampling rate is low.

(4) The sampling rate (1500 Hz) used for the digital controller was sufficiently high compared with the system resonant frequency (15 Hz) for the zero-order hold and the computing time delay to have insignificant adverse phase effects. The frequency margin permitted the use of a low-pass anti-aliasing filter which gave satisfactory high frequency noise attenuation without adverse phase effects. A lower sampling frequency could have been used without significant deterioration of the suspension damping.

It is worth noting that when choosing the minimum sampling rate for this system the phase implications must be carefully considered in order that the suspension system maintains wide stability margins. The lowering of the sampling rate will normally imply lowering the pass band of the anti-aliasing filter, and both will have adverse phase effects.

(5) The ease of writing the software for the controller would be improved by the use of a fast floating-point facility. The constraint of fixed point arithmetic has necessitated care in achieving suitable scalings to avoid overflow and to maintain good resolution throughout.

5. Summary and Future Developments

5.1 Summary

Digital control of a magnetically suspended model has proved possible albeit with an increase in the ambient model motion due to noise.

Sensor noise entering the noise-sensitive controller has contributed a negligible amount to the increase in model motion. This is primarily due to the use of a high sampling frequency (1500 Hz) compared with the system natural frequency (15 Hz), allowing large attenuation of noise by an anti-aliasing filter.

The major source of noise is thought to be the controllers' D/A converter. This is aggravated because it feeds a power amplifier which has a low frequency (150 Hz) thyristor-switching control. This situation is particular to the suspension system currently in use and should be improved by the following developments.

5.2 Future Developments

The following developments impinge directly upon the controller development.

The plant hardware is being modified in that:-

- (i) the magnetic coil configuration is being altered.
- (ii) the power amplifiers are being replaced with units having a much increased switching frequency. This should allow a major reduction in the ambient model motion.

The controller hardware is being modified by the replacement of its D/A. As a consequence of the work reported here its noise specification will be reviewed.

Alternative direct-digital control of power to the coils is worth exploring.

A less noise-sensitive control algorithm is being developed, suitable

for analogue or digital control.

Digital control is being extended to all six degrees of freedom.

Appendix A

Difference Equation Form of a Phase Advance Transfer Function

The transfer function $\frac{z}{u} = \frac{1 + n T D}{1 + T D}$

may be separated into denominator and numerator and shown in sequential form as:-



Denominator

Thus $T \frac{dy}{dt} = u - y$ leads to $\Delta y = (u - y) \frac{\Delta t}{T}$

and so

$$T \cdot \Delta y(k) = \Delta t u(k) - \Delta t y(k-1) \quad (A.1)$$

Since

$$\Delta y(k) = y(k) - y(k-1)$$

then

$$T y(k) = \Delta t u(k) + (T - \Delta t) y(k-1) \quad (A.2)$$

Numerator

Also since $\frac{z}{y} = 1 + n T D$

then

$$z(k) = y(k) + \frac{nT}{\Delta t} \Delta y(k) \quad (A.3)$$

PROGRAM LISTING

SOUTHAMPTON UNIVERSITY WERS FACILITY

DIGITAL CONTROLLERS FOR THE VERTICAL CHANNELS

INITIALIZATION

OUT=167774
CLS=170404
CLB=170406
AUSR=170402
AUSR=170400

TEST:

MOV #0,0#177546
MOV #176545,CLB
MOV #3,CLS

LOOP:

TSIB CLS
DPL LOOP
MOV #3,CLS
MOV #1,ADSR
TSIB ADSR
BPL L1

L1:

FIRST STAGE (VERTICAL HEAVE)

IN:

MOV ADPR,RO
SUB #2048,RO
ASH #2,RO
MOV RO,RS
SXT R4

INPUT ROUTINE W.H.

$$\Delta_1 = z^*(k) - y_1(k-1)$$

$$y_1(k) = \{z^*(k) + 5y_1(k-1)\} / 6$$

$$y_2(k) = \{y_1(k) + 8.\Delta_1\} / 2$$

SECOND STAGE (VERTICAL HEAVE)

```

SEC:  MOV    R0,R5
      SXT    R4

      MOV    LT2,R2
      SUB    R2,R0
      MUL    #5.,R2
      ADD    R5,R3
      ADC    R2
      ADD    R4,R2
      ADD    #3,R3
      ADC    R2
      DIV    #6.,R2
      MOV    R2,LT2
      MOV    #1,ADSR

```

$$\Delta_2 = y_2(k) - y_3(k-1)$$

$$y_3(k) = \{y_2(k) + 5y_3(k-1)\} / 6$$

```

      ASH    #3,R0
      ADD    R2,R0

```

$$E(k) = y_3(k) + 8.\Delta_2$$

```

      ADD    #2048.,R0
      BMI    L2
      CMP    #4095.,R0
      BMI    L3
      MOV    R0,OUT
      BR     PITCH
L2:    MOV    #0,OUT
      BR     PITCH
L3:    MOV    #4095.,OUT

```

OUTPUT ROUTINE V.H.

FIRST STAGE (VERTICAL PITCH)

```

PITCH: TSTB   ADSR
      BPL     PITCH

```

```

NF:    MOV    ADDR,R0
      SUB    #2048.,R0
      ASH    #3,R0
      MOV    R0,R5
      SXT    R4

```

INPUT ROUTINE V.P.

```

      MOV    PT1,R2
      SUB    R2,R0
      MUL    #10.,R2
      ADD    R5,R3
      ADC    R2
      ADD    R4,R2
      DIV    #11.,R2
      MOV    R2,PT1
      ASH    #-2,R2
      ADD    R2,R0

```

$$\Delta_1 = 80^*(k) - y_1(k-1)$$

$$y_1(k) = \{80^*(k) + 10y_1(k-1)\} / 11$$

$$y_2(k) = \frac{y_1(k)}{4} + \Delta_1$$

SECOND STAGE (VERTICAL FITCH)

```
MOV    R0,R5
SXT    R4
```

```
MOV    PT2,R2
SUB    R2,R0
MUL    #5,R2
ADD    R5,R3
ADC    R2
ADD    R4,R2
DIV    #6,R2
MOV    R2,PT2
```

$$\Delta_2 = y_2(k) - y_3(k-1)$$

$$y_3(k) = \{y_2(k) + 5y_3(k-1)\} / 6$$

```
ASH    #3,R0
ADD    R2,R0
ASH    #-6,R0
```

$$E(k) = \{y_3(k) + 8\Delta_2\} / 64$$

```
ADD    #120,R0
BMI    PL2
CMP    #250,R0
BMI    PL3
MOV    R0,ADBR
JMP    LOOP
PL2:   MOV    #0,ADBR
JMP    LOOP
PL3:   MOV    #250,ADBR
JMP    LOOP
```

OUTPUT ROUTINE

```
LT0:   .WORD  0
LT1:   .WORD  0
LT2:   .WORD  0
PT0:   .WORD  0
PT1:   .WORD  0
PT2:   .WORD  0
.END   TEST
```


References

- Ref 1. "The Magnetic Suspension of Wind Tunnel Models"
M. J. Goodyer, ASU Report, 1968

FIG. 1

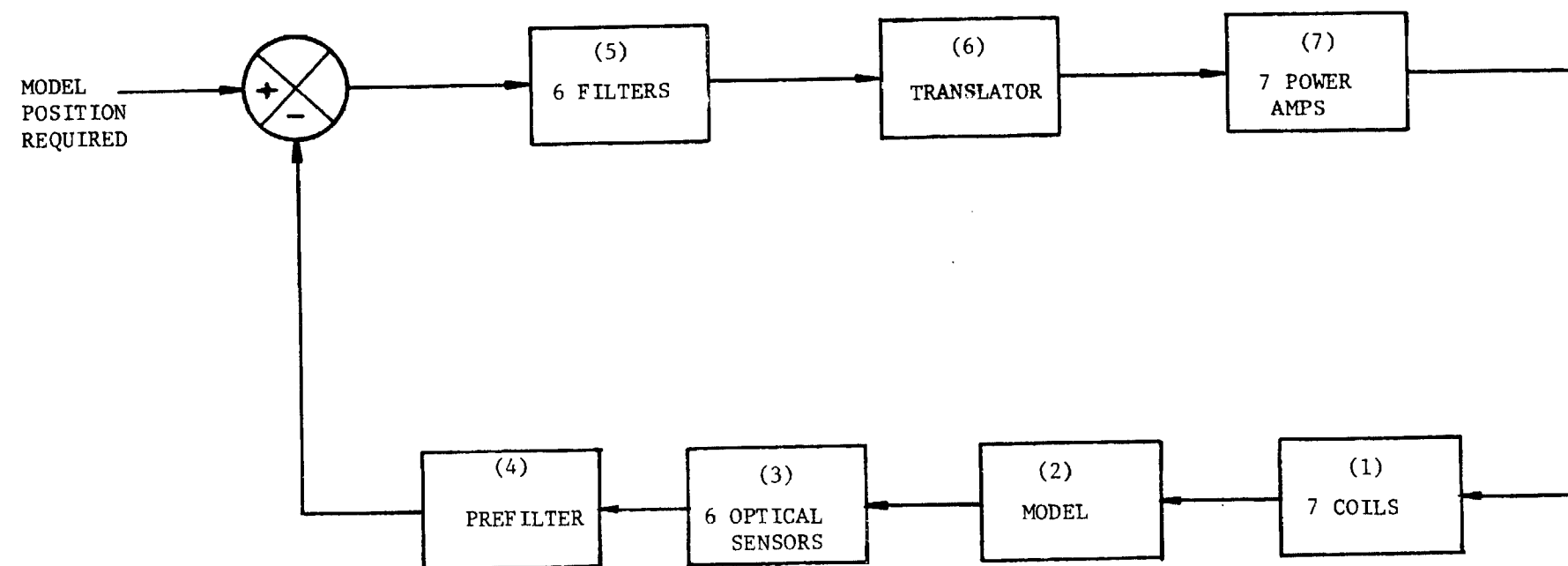
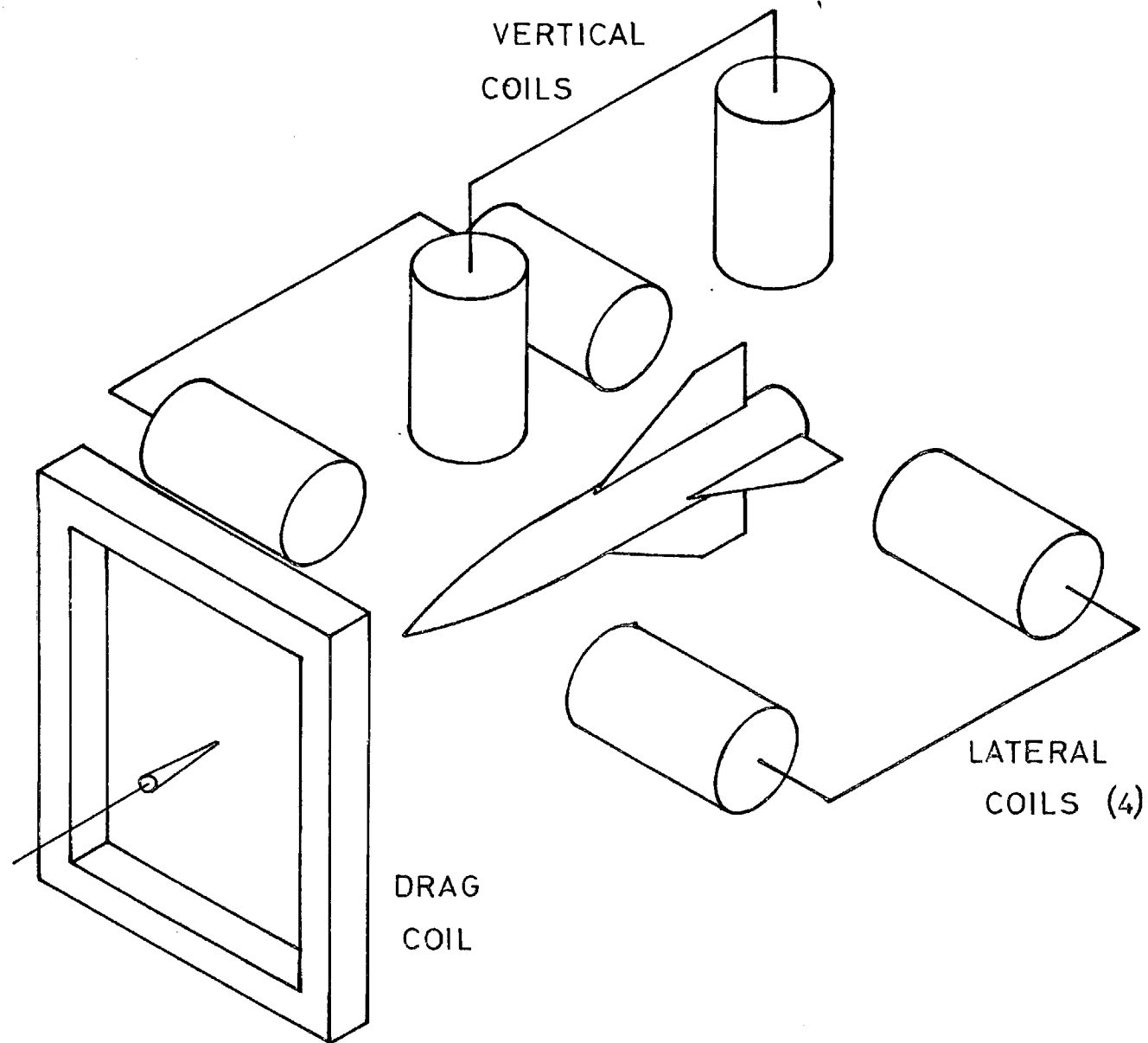


FIG. 1 BLOCK DIAGRAM OF SUSPENSION SYSTEM

FIG. 2



COIL ARRANGEMENT

FIG. 2

FIG. 3

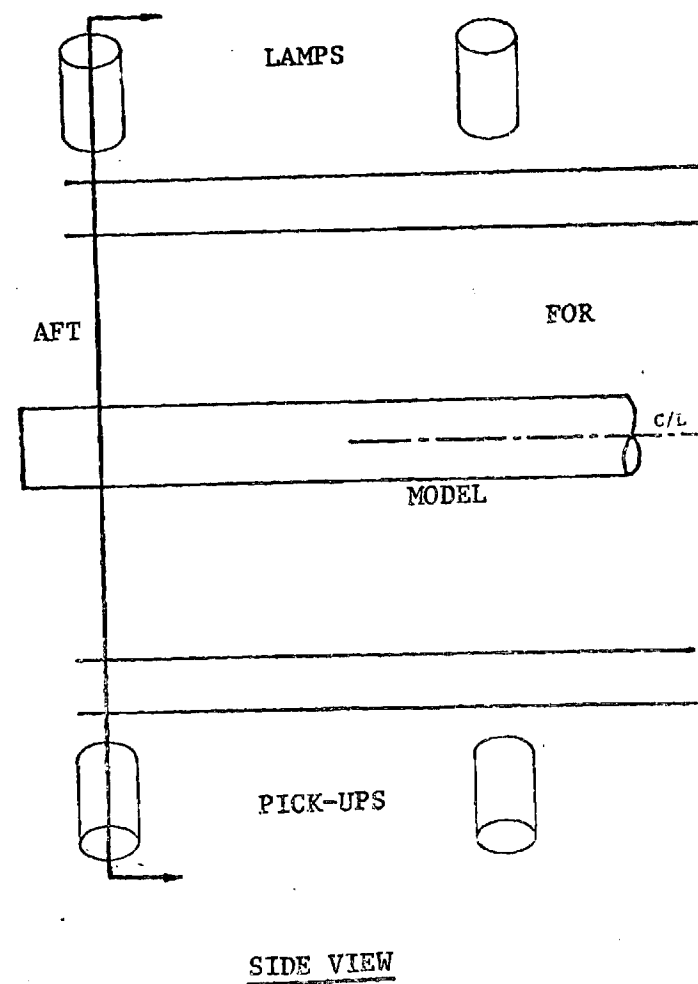
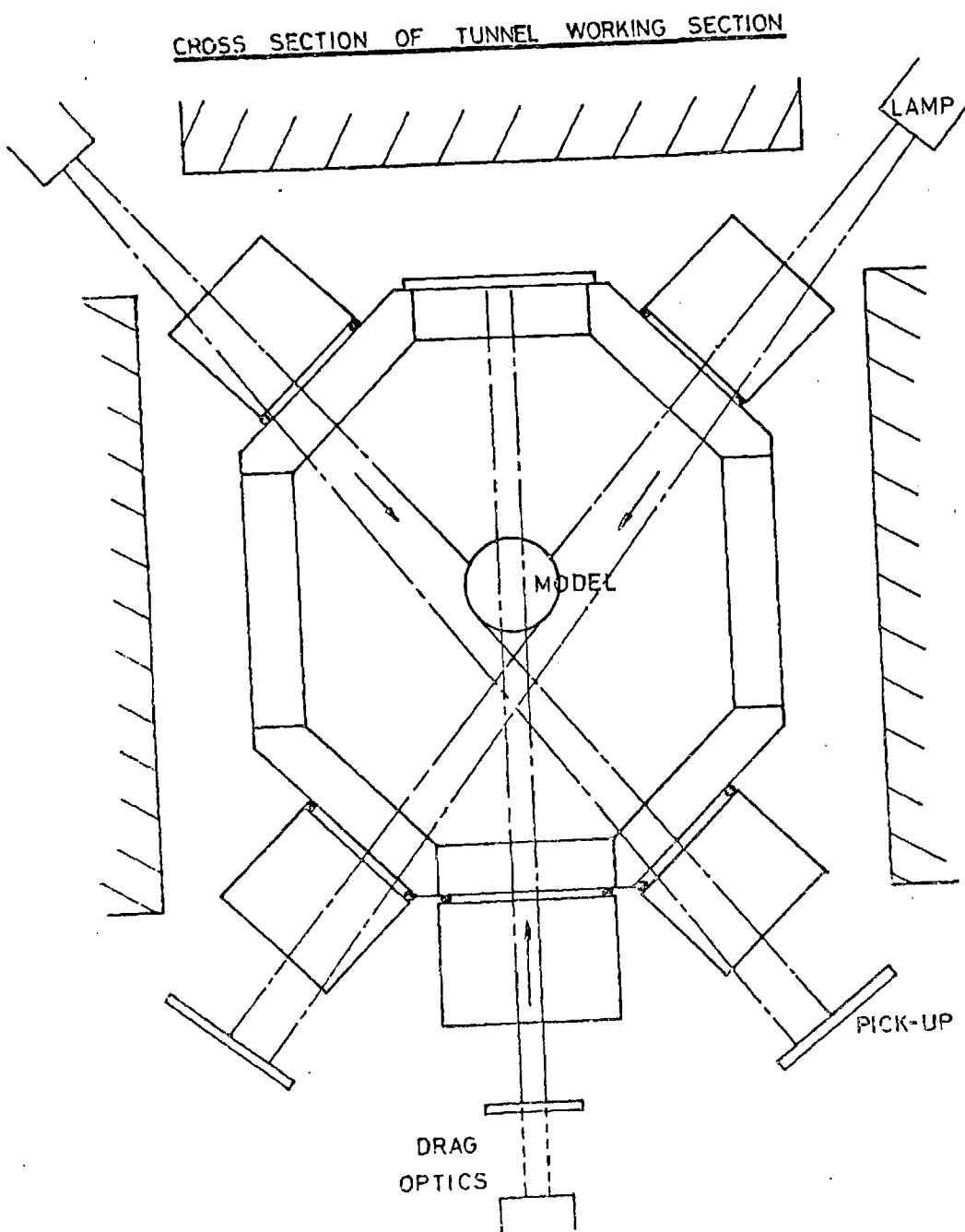
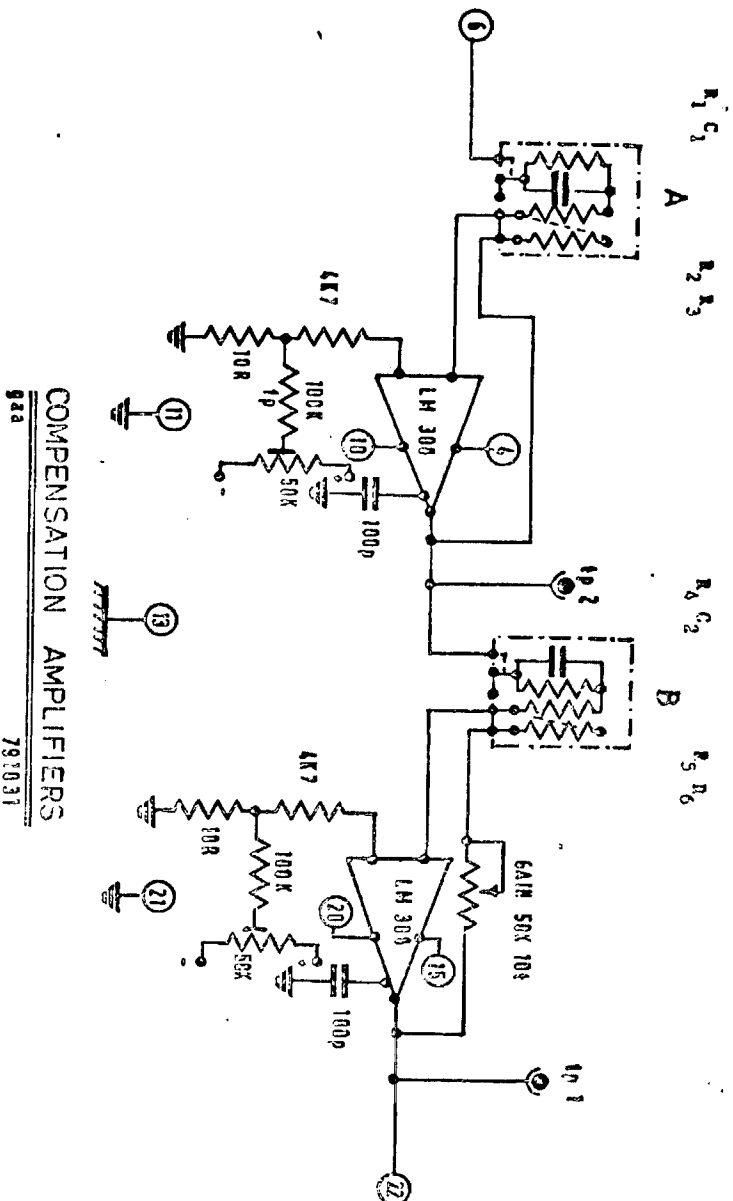


FIG. 3 OPTICAL SENSOR ARRANGEMENT

FIG. 4



VERTICAL HEAVE

$R_1 = 68K$
 $R_2 = 8K2$
 $R_3 = 28K$
 $C_1 = .47\mu$

$R_4 = 33K$
 $R_5 = 3K9$
 $R_6 = 5K7$
 $C_2 = 1\mu$

VERTICAL PITCH

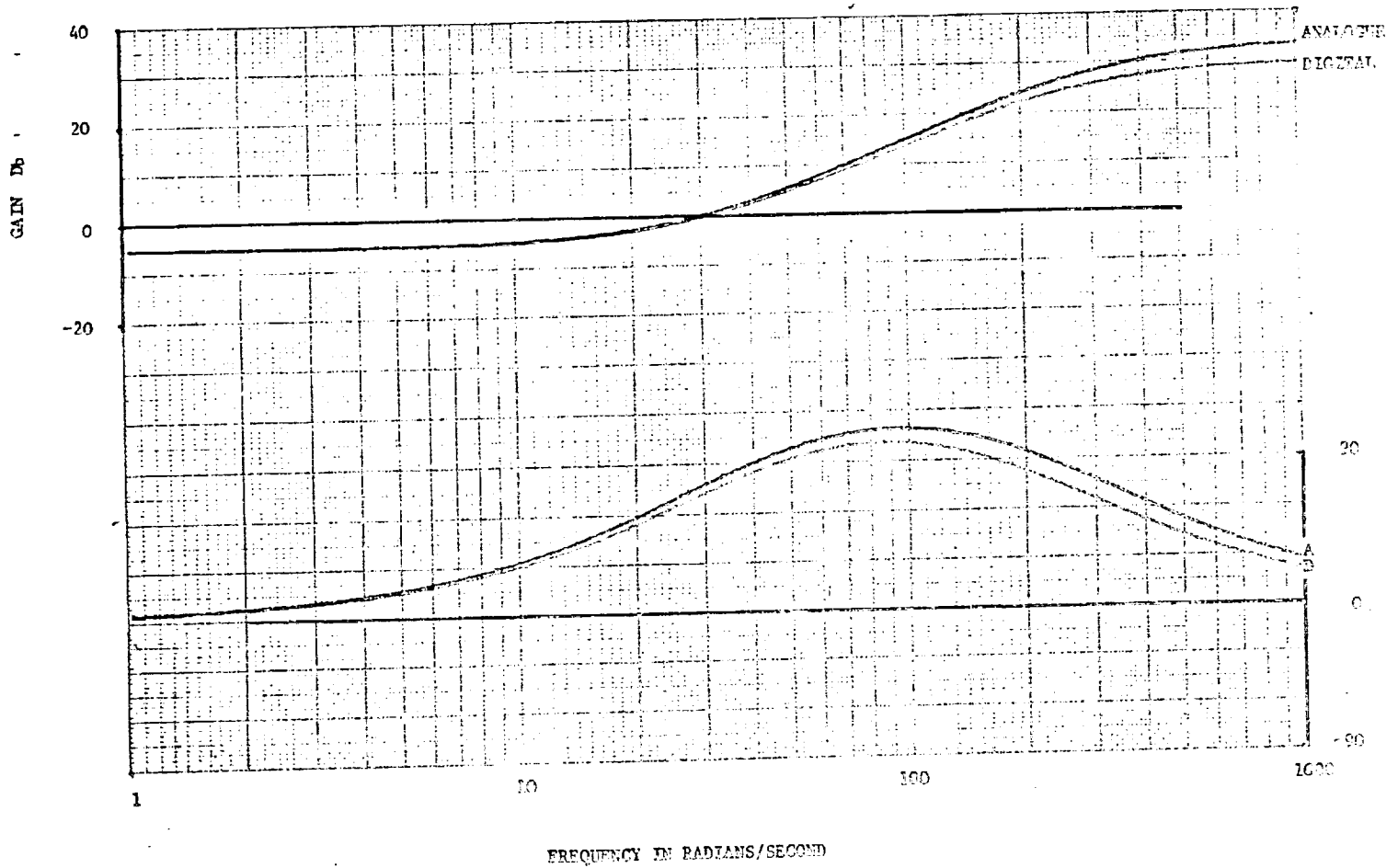
$R_1 = 33K$
 $R_2 = 3K9$
 $R_3 = 7K8$
 $C_1 = 1\mu$

$R_4 = 78K$
 $R_5 = 18K$
 $R_6 = 68K$
 $C_2 = .47\mu$

ANALOGUE CONTROLLER CIRCUITS FIG. 4

FIG. 5

LOG 3 CYCLES PER INCH, 1/3 IN



ANALOGUE FILTER

$$\frac{E}{Z} = \frac{1}{2} \left[\frac{1 + .033 D}{1 + .0033 D} \right]^2$$

DIGITAL FILTER

$$\frac{E}{Z} = \frac{1}{2} \left[\frac{1 + .033 D}{1 + .004 D} \right]^2$$

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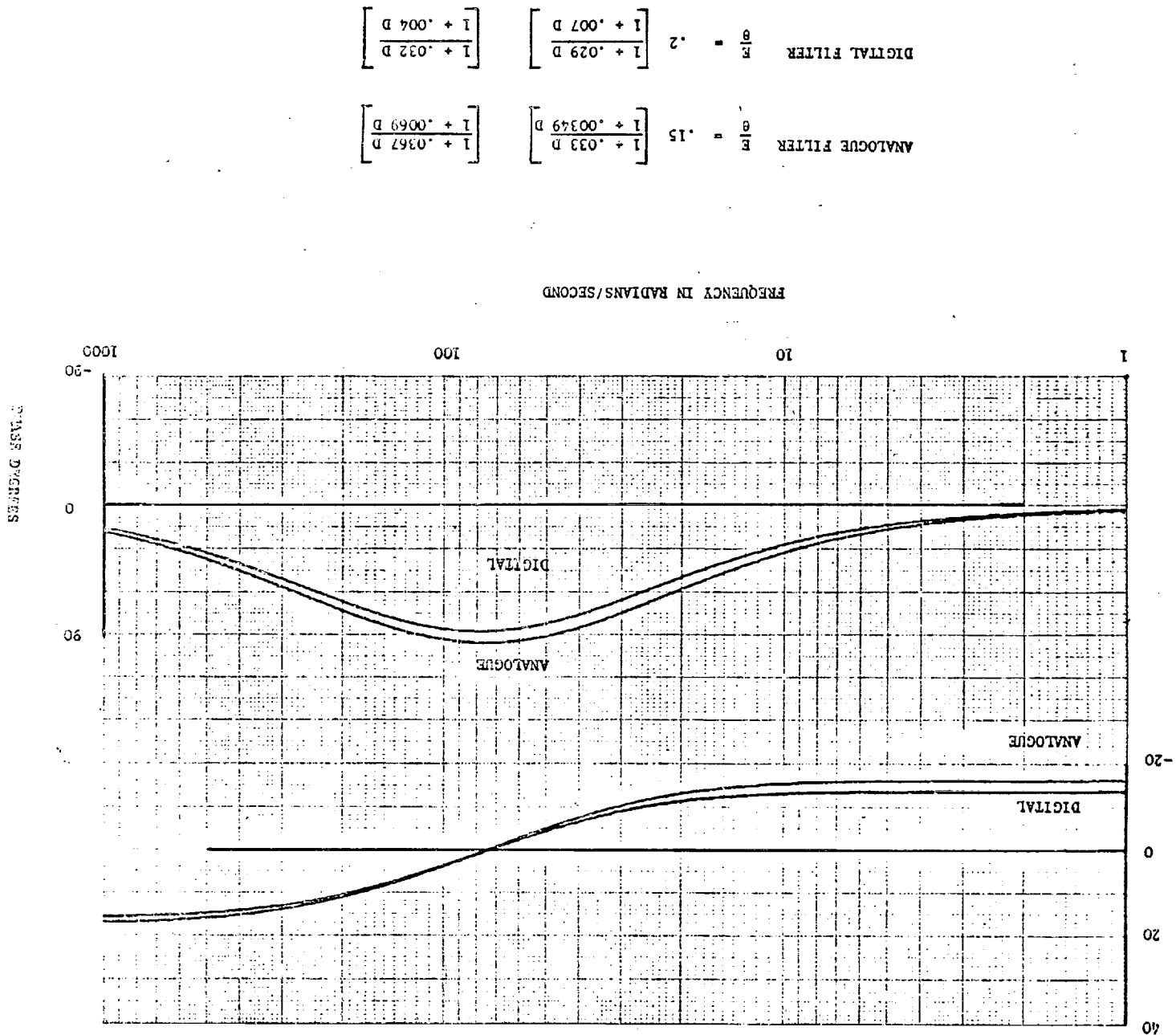
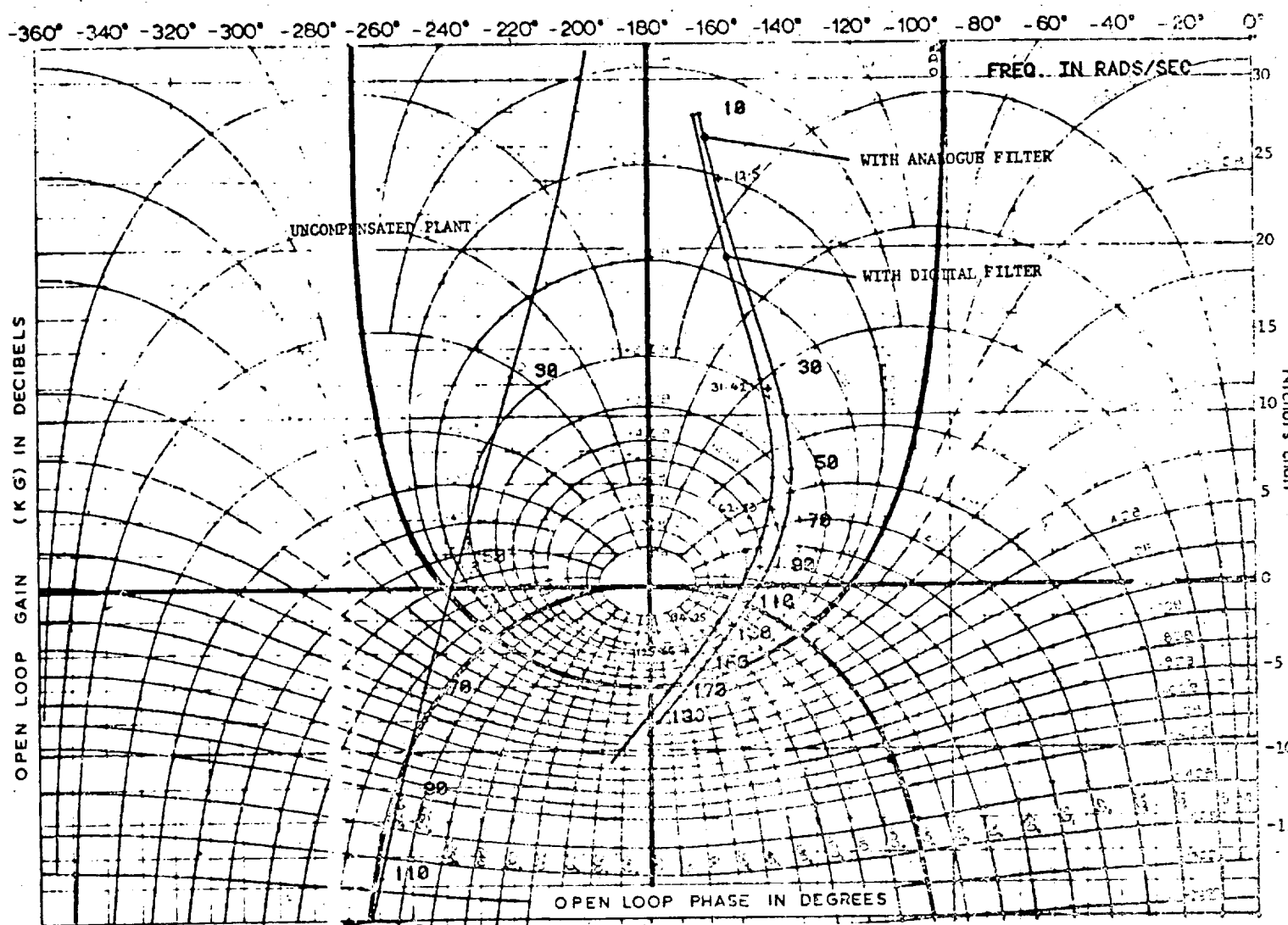


FIG. 7



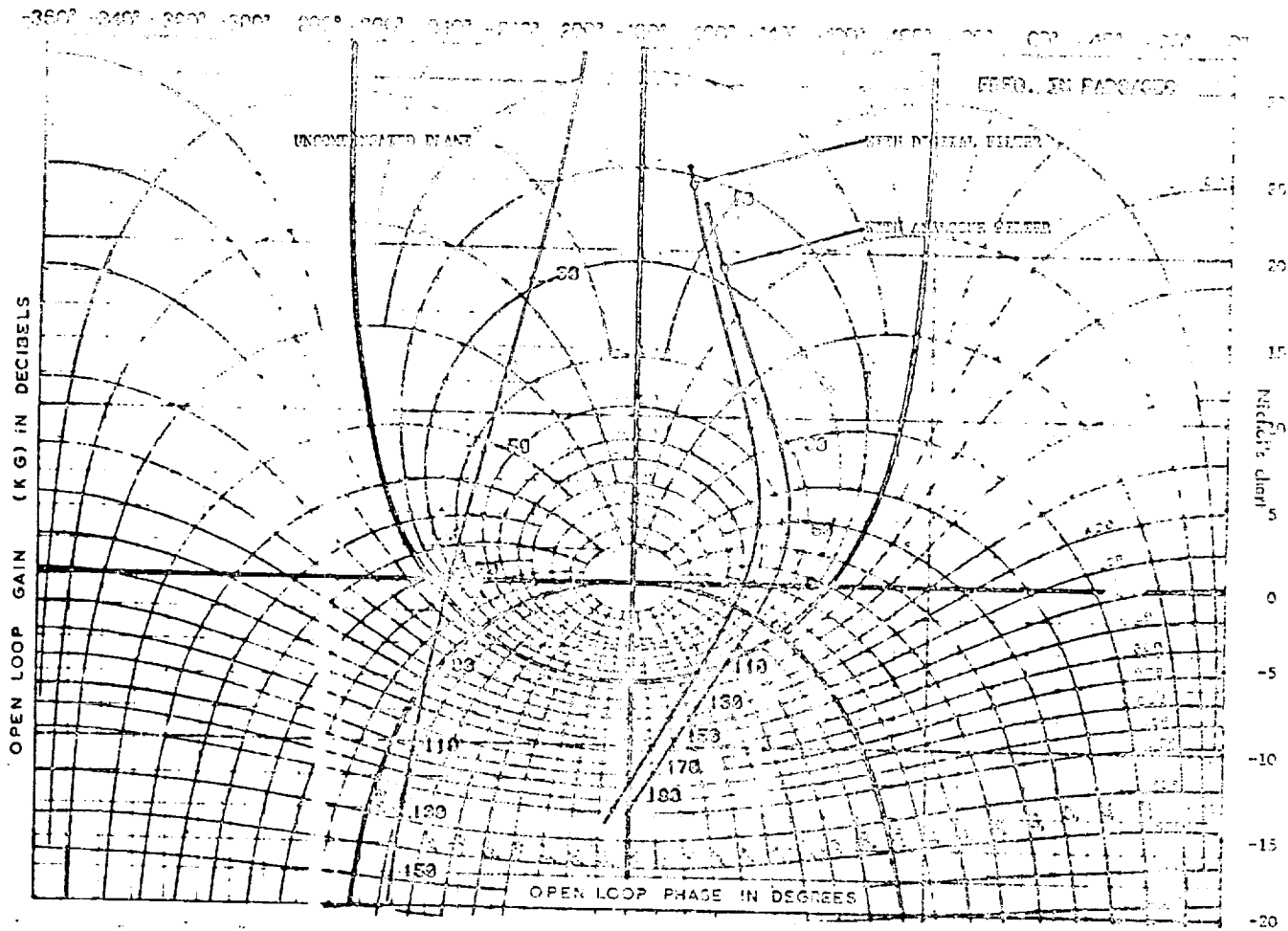
$$\text{UNCOMPENSATED PLANT T.F. } G(D) = \frac{4730}{D^2 \left(1 + \frac{D}{40}\right) \left(1 + \frac{D}{600}\right)}$$

$$\text{ANALOGUE FILTER } \frac{E}{Z} = \frac{1}{2} \left[\frac{1 + .033 D}{1 + .0033 D} \right]^2$$

$$\text{DIGITAL FILTER } \frac{E}{Z} = \frac{1}{2} \left[\frac{1 + .033 D}{1 + .004 D} \right]^2$$

EXPERIMENTAL DATA
WITH ANALOGUE FILTER

FIG. 8



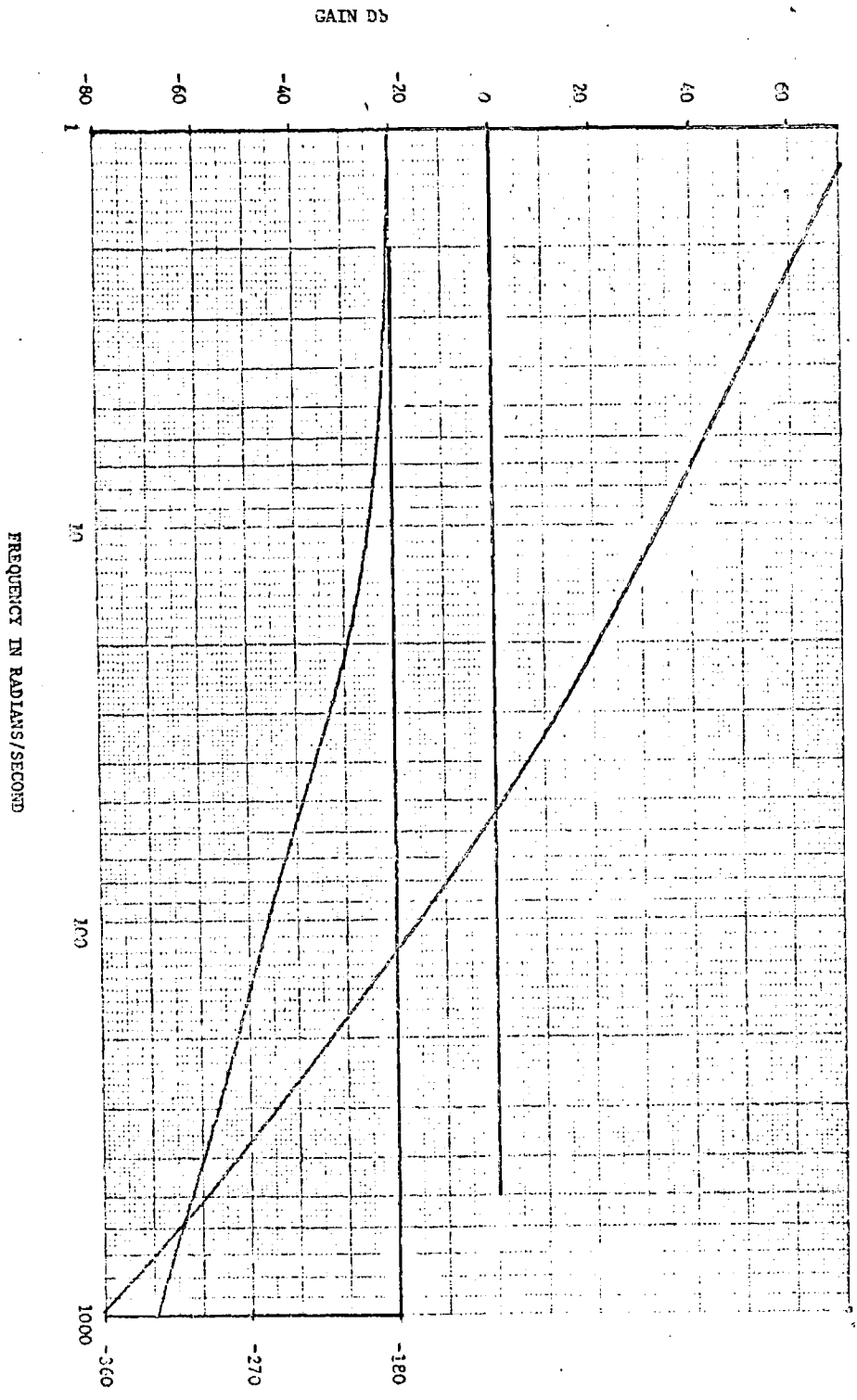
$$\text{UNCOMPENSATED PLANT T.F. } G(D) = \frac{8500}{D^2(1 + .02 D)}$$

$$\text{ANALOGUE FILTER } \frac{E}{\theta} = .15 \left[\frac{1 + .033 D}{1 + .00349 D} \right] \left[\frac{1 + .0367 D}{1 + .0069 D} \right]$$

$$\text{DIGITAL FILTER } \frac{E}{\theta} = .2 \left[\frac{1 + .029 D}{1 + .007 D} \right] \left[\frac{1 + .032 D}{1 + .004 D} \right]$$

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FIG. 9



$$\text{UNCOMPENSATED PLANT T.F. } G(D) = \frac{4730}{D^2 \left(1 + \frac{D}{40}\right) \left(1 + \frac{D}{600}\right)}$$

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FIG. 10

100 X CYCLES X INCH 1.0 1 CM

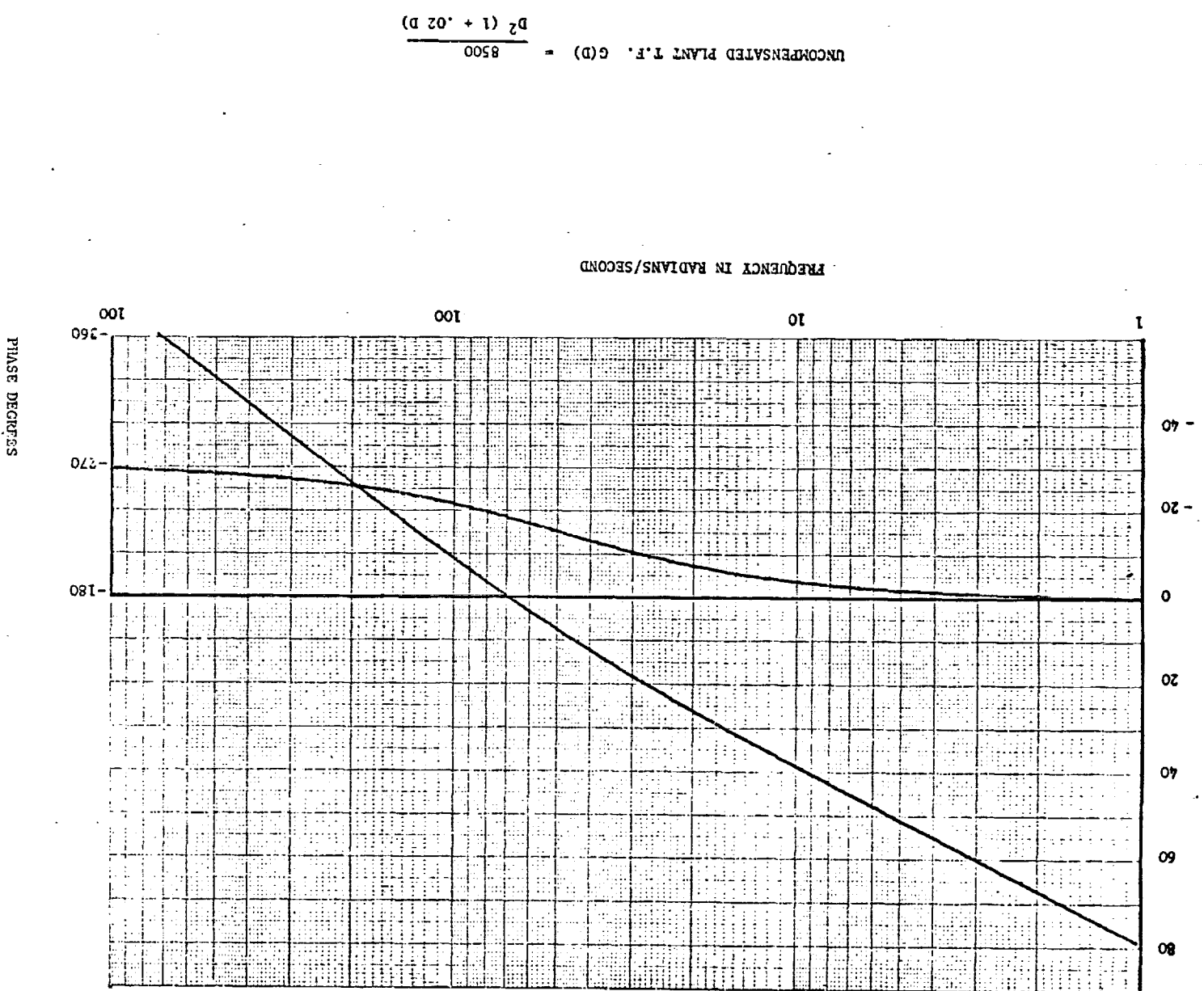
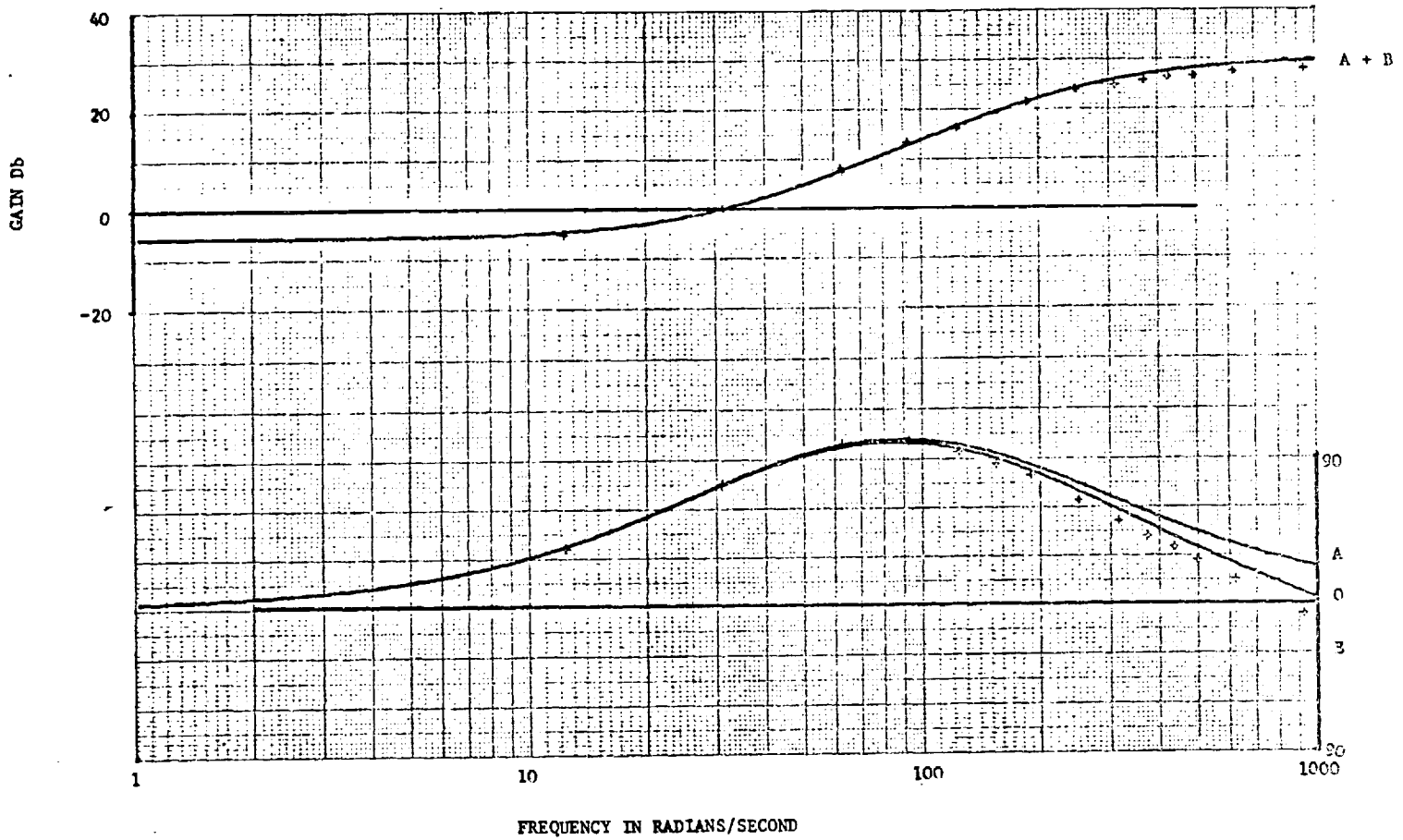


FIG. 11

LOG 3-CYCLES X mm. 3.6 1 cm



A) DIGITAL FILTER $\frac{E}{z} = \frac{1}{2} \left[\frac{1 + .033 D}{1 + .004 D} \right]^2$

B) DIGITAL FILTER (INCLUDING ZERO ORDER HOLD) $\frac{E}{z} = \frac{1}{2} \left[\frac{1 + .033 D}{1 + .004 D} \right] \left[\frac{-e^{-\frac{D}{1500}}}{D} \right]$

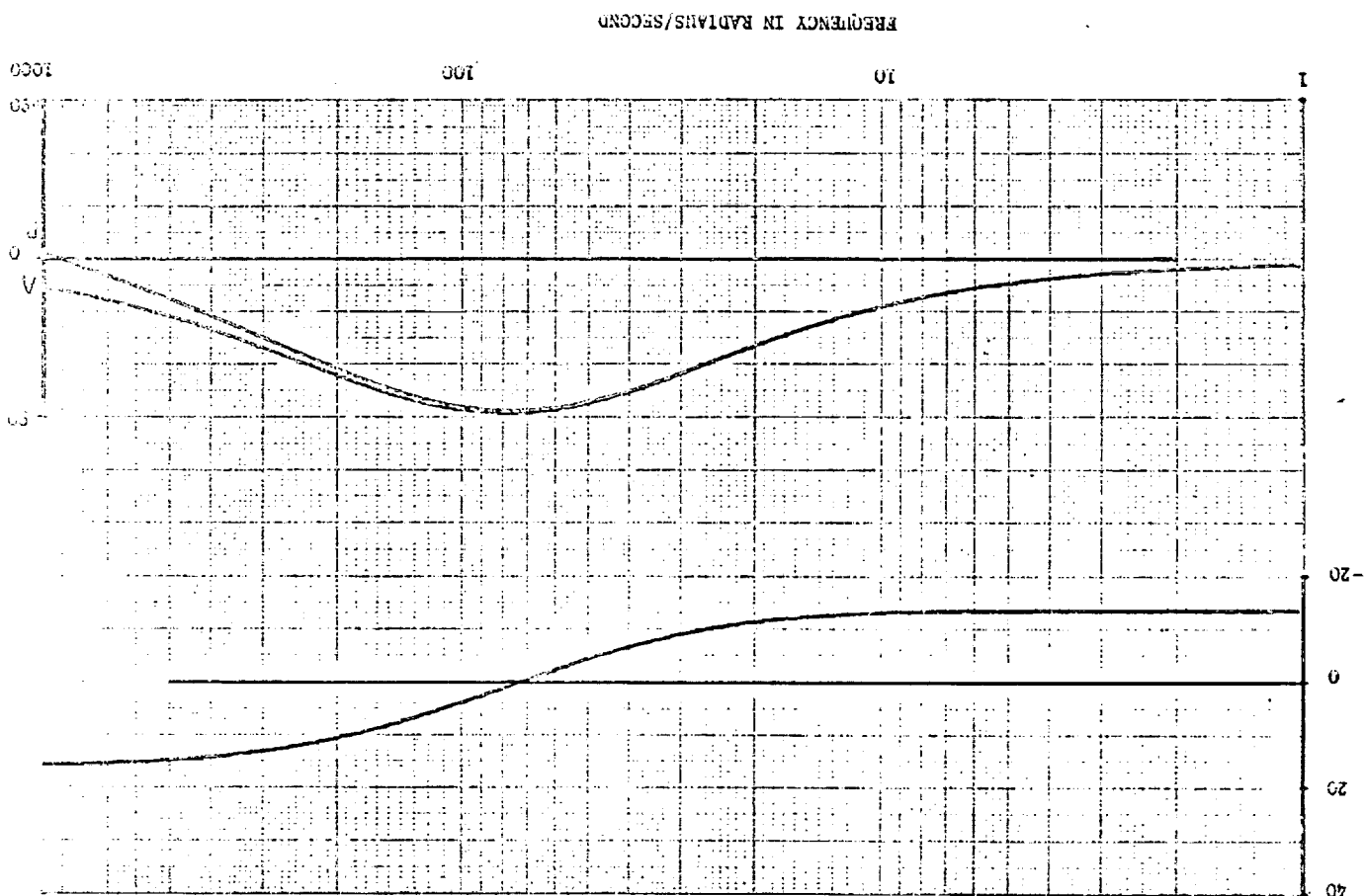
EXPERIMENTAL POINTS

+ + +

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A) DIGITAL FILTER $\frac{e}{E} = .2 \left[\frac{1 + .029 D}{1 + .006 D} \right] \left[\frac{1 + .007 D}{1 + .033 D} \right] \left[\frac{1 - e^{-\frac{1}{1000} D}}{1 - e^{-\frac{1}{1000} D}} \right]$

B) DIGITAL FILTER (INCLUDING ZERO ORDER HOLD) $\frac{e}{E} = .2 \left[\frac{1 + .029 D}{1 + .006 D} \right] \left[\frac{1 + .007 D}{1 + .033 D} \right] \left[\frac{1 - e^{-\frac{1}{1000} D}}{1 - e^{-\frac{1}{1000} D}} \right]$



100 X 1000 X 1000 X 1000

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| 1. Report No. NASA CR-165684 | | 2. Government Accession No. | | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle Digital Controllers for the Vertical Channels of a Magnetic Suspension System | | | | 5. Report Date May 1981 | |
| | | | | 6. Performing Organization Code | |
| 7. Author(s) P. W. Fortescue and C. Bouchalis | | | | 8. Performing Organization Report No. | |
| | | | | 10. Work Unit No. | |
| 9. Performing Organization Name and Address The University of Southampton Department of Aeronautics and Astronautics Southampton SO9 5NH, England | | | | 11. Contract or Grant No. NSG-7523 | |
| | | | | 13. Type of Report and Period Covered Contractor Report 11-1-79 to 11-1-80 | |
| 12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546 | | | | 14. Sponsoring Agency Code 505-31-53-02 | |
| | | | | | |
| 15. Supplementary Notes Principal Investigator was Dr. M. J. Goodyer. Langley Technical Monitor was Richmond P. Boyden. | | | | | |
| 16. Abstract The Southampton University Magnetic Suspension System has an analog controller which is being replaced by a digital filter. The report covers the first stage of conversion in which two of the six degrees of freedom, viz vertical heave and pitch have been fitted with a digital version of the analog filters. Direct replacements for the analog phase advance filters were used and performance comparisons were made. In addition, a mathematical model of the magnetic coils and suspended model was developed for future small angle use. | | | | | |
| 17. Key Words (Suggested by Author(s)) Magnetic suspension Digital control Digital filter | | | | 18. Distribution Statement Unclassified - Unlimited Star Category - 09 | |
| 19. Security Classif. (of this report) Unclassified | | 20. Security Classif. (of this page) Unclassified | | 21. No. of Pages 33 | |
| | | | | 22. Price A03 | |

